Steel Industry
Energy Bandwidth Study

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for the
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Industrial Technologies Program

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Overview

The Industrial Technologies Program (ITP) within DOE's Office of Energy Efficiency and Renewable Energy has developed a series of quantitative analyses to help characterize opportunities for improving energy efficiency in key manufacturing process streams. These include:

- An energy "bandwidth" analysis that identifies the theoretical minimum amount of energy required for each major operation within a given industry, the current amount of energy that is used in that operation, and the difference between the two (the "bandwidth")
- An industry "footprint" that characterizes an industry's energy use according to unit operation, showing how much energy is used for process heating, electric motors, pumping, etc.

Together, the bandwidth and the footprint analysis can be used to project the potential energy savings available at the plant process level. Unlike the programmatic metrics developed each year in accordance with the Government Performance and Results Act (GPRA), which are based on the projected estimated savings of individual R&D projects, the bandwidth/footprint provides a projected potential savings at the application level and is thus a broader metric.

The purpose of a bandwidth study is to provide a realistic estimate of the potential amount of energy that can be saved in an industrial process. The bandwidth refers to the difference between the amount of energy that would be consumed in a process using commercially available technology versus the minimum amount of energy needed to achieve those same results based on the 2nd law of thermodynamics.

The data required to construct the steel industry energy bandwidth were developed in several studies sponsored by ITP:

- *Theoretical Minimum Energies to Produce Steel for Selected Conditions* by R.J. Fruehan, et al., published in September 2000
- *Energy Use in the U.S. Steel Industry: A Historical Perspective and Future Opportunities* by J. Stubbles, September 2000
- *Energy and Environmental Profile of the U.S. Steel Industry* by Energetics, Inc., published in August 2000

The steel industry energy bandwidth analysis also estimates steel industry energy use in the year 2010 and uses that value as a basis for comparison against the minimum requirements. This energy savings opportunity for 2010 may provide a better baseline for many ITP program planning efforts because of the program's focus on longer term R&D.

Table 1 provides a summary of the input data required for the bandwidth and the primary source of those data.

Table 1. Summary of Data Required to Construct the Steel Industry Energy Bandwidth		
Data	**Source(s)**	**Table Below**
Theoretical minimum energy requirements	Fruehan	2, 3,4
Practical minimum energy requirements	Fruehan	2,3,4
Current energy use by unit operation	Stubbles Fruehan Energetics	2,3,5
2010 energy use estimates	Stubbles	6

The major steel industry processes for which a bandwidth comparing estimated 2010 energy requirements versus minimum energy requirements was constructed include:

- Ironmaking
- BOF steelmaking
- EAF steelmaking
- Reheating/hot rolling

As shown in Table 1, both Fruehan and Stubbles estimated current process energy intensity. Fruehan's estimates reflect an overall industry average, while Stubbles' values represent "good practices" that are "better than average but not the best." The "good practice" values were used as the starting point for predicting energy use in the steel industry in 2010.

Theoretical and Practical Minimum Energy Requirements for Steel Industry Processes

In his September 200 report, *Theoretical Minimum Energies to Produce Steel for Selected Conditions*, R.J. Fruehan presents the theoretical minimum energy required to produce steel from ore and mixtures of scrap and scrap alternatives (see Table 2). Additional cases in which the assumptions are changed to more closely approximate actual operating conditions were also analyzed, yielding the "practical minimum" values shown in Table 2. The results were subsequently used in the bandwidth analysis to determine the theoretical and practical potentials for reducing steelmaking energy requirements.

Table 2. Fruehan Study Results: Comparison of Theoretical Minimum Energy and Actual Energy Requirements for Selected Processes (Note: all values exclude electrical generation and transmission losses)					
Process	**Energy (10^6 Btu/ton)**				
	Actual Requirements[a]	**Theoretical Minimum**	**Difference (Actual vs Theo Min)**	**Practical Minimum**	**Difference (Actual vs Pract Min)**
Liquid Hot Metal (5%C)	11.2 - 12.1	8.5	25 – 30%	9.0	20 – 26%
Liquid Steel (BOF)[b]	9.1 - 9.9	6.8	25 – 31%	7.1	22 – 29%
Liquid Steel (EAF)	1.8 - 2.1	1.1	38 - 46%	1.4	24 – 33%
Hot Rolling Flat	1.7 - 2.1	0.03	99%	0.8	55 – 63%
Cold Rolling Flat	0.9 - 1.2	0.02	98 – 99%	0.02	98 – 99%
18-8 Stainless Melting	--	1.0	--	1.3	--

a Actual includes yield losses and is the average of state-of-art and less-efficient operations for the United States, Japan, and Europe

b BOF energy is primarily from hot metal; actual process consumes 0.2 to 0.4 10^6 Btu/ton and, if CO is oxidized to CO_2, could theoretically produce 0.4 10^6 Btu/ton.

Several significant sources of energy consumption were neglected in computing the theoretical minimum energies to produce steel, including cokemaking and ore agglomeration. In theory, agglomeration and cokemaking are not necessary for integrated steel production; however, they are virtually always part of actual integrated steelmaking. The approximate minimum energies for these processes, along with typical actual consumptions, are given in Table 3.

Table 3. Fruehan Study Results: Theoretical Minimum and Typical Energy Consumption in Cokemaking and Ore Agglomeration				
Process	**Theoretical Energy**		**Actual Energy**	
	10^6 Btu/ton of output	**10^6 Btu/ton of steel**	**10^6 Btu/ton of output**	**10^6 Btu/ton of steel**
Cokemaking[a]	1.7	0.7	4.7 – 5.6	1.9 – 2.2
Ore Agglomeration[b]	1.0	1.4	1.3 – 1.5	1.8 – 2.1

a Full credit is taken for off gas and by-product energy (approximately 3.8 – 5.7 10^6 Btu).

b Does not include energy associated with ore extraction and other processes prior to agglomeration.

Fruehan also estimated the theoretical minimum energy required to roll steel. Steel can be hot or cold rolled; with hot rolling, the steel either is reheated or directly charged after casting. Reheating is the major energy consumer in the rolling process. The analysis considered hot and cold rolling for flat rolled carbon steel and 18-8 type stainless (starting from both normal slabs and thin slabs), as well as hot rolling of bars from billet (see Table 4).

Table 4. Fruehan Study Results: Theoretical Minimum Energies to Roll Steel for Selected Products and Conditions

Rolling Type	Rolling Temperature (K)	Slab Temperature[a] (K)	Reduction (mm)	Energy (10^6 Btu/ton)		
				Heat	Deform-ation	Total
Flat Carbon Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	711	22	733
Hot	1473	1173	254 to 2	233	22	255
Hot	1473	1473	254 to 2	--	22	22
Cold	298	298	2 to 1	--	15	15
Flat Carbon Slab (5.0 cm or 1.97 inch)						
Hot	1473	298	50 to 2	711	14	725
Hot	1473	1173	50 to 2	233	14	247
Hot	1473	1473	50 to 2	--	13	14
Cold	298	298	2 to 1	--	15	15
Flat 18-8 Stainless Steel Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	711	62	773
Hot	1473	1173	254 to 2	234	62	296
Hot	1473	1473	254 to 2	--	62	62
Cold	298	298	2 to 1	--	44	44
Bar Carbon (10 cm billet to 2 cm bar)						
Hot	1473	298	10 sq to 2 sq	711	17	728
Hot	1473	1473	10 sq to 2 sq	--	17	17
Hot	1473	1173	10 sq to 2 sq	233	17	250
Hot[b]	1473	1473	10 sq to 2 sq	--	9	9

a Slab temperature prior to rolling
b Billet split into four pieces prior to rolling

"Good Practice" Energy Use and Predictions for 2010

Stubbles estimated the "good practice" energy use associated with ironmaking, steelmaking, and finishing in the integrated and EAF industry sub-sectors. Good practice operations are defined as ones that are sustainable and have been developed around technology that is commercially available. For example, good practices would include thin slab but not thin strip casting. Table 5 illustrates the breakdown between primary and finishing operations for good practice data.

Stubbles also projected energy intensity and potential savings for the period 2000 to 2010 based on a combination of technology advances and structural changes to the U.S. steel industry.

A number of *technological developments* will impact the future energy consumption by the U.S. steel industry:

- Coal-based, onshore, alternate ironmaking production
- Non-recovery coke production
- Direct smelting
- Thin strip casting
- Increased efforts to conserve energy in hot cast products;
- Increased efforts to capture chemical energy in waste gases from processes;
- Increased use of sensors in all operations to improve efficiency;
- Implementation of the motor challenge program.

New technology spurs *structural change* that affects overall industry energy intensity. Established companies may go out of business in part because they have failed to modernize and are then replaced by new companies that have adopted the latest technology and different processes.

For example, since the beginning of WWII, the open hearth steelmaking furnace along with ingot casting and blooming mills have all been replaced by the basic oxygen process, continuous casting, and the modern EAF. The result has been a huge increase in yield from raw steel to shipped product, as well as the adoption of less energy intensive processes such as the EAF steelmaking. Energy consumption per ton has plummeted from over 40 MBtu to less than 20 MBtu/shipped ton in two generations. Because of such effects, identifying factors that drive the industry towards specific processes and away from others is important in assessing overall energy consumption in the future.

Stubbles' projections, which extend through 2010, are based on the following predictions:

- *Net Imports* will decline to about 25 million tons if the world economy remains stable and demand for steel outside the United States increases.
- *Integrated Mills* will decline to 50 million tons of shipments.
- *EAF Conventional Mills* will experience a slight decline as some of the smaller mills close due to age and production of a non-competitive product line.
- *EAF Flat Rolled* output will double with 40 percent opting for on-site AI production of either hot metal or hot sponge iron to increase productivity for a given shop.

Table 5. Stubbles Study Results: Summary of Good Practice Energy Use by the U.S. Steel Industry, 1998[a,b]			
Ironmaking			
	Amount (10^6 tons)	**Energy Intensity (10^6Btu/ton)**	**Total Energy Use (10^{12} Btu)**
Integrated	53.0	15.5	822
EAF-Flat Rolled	n/a	n/a	n/a
EAF-Other	n/a	n/a	n/a
Total			*822*
Steelmaking			
	Amount (10^6 tons)	**Energy Intensity (10^6 Btu/ton)**	**Total Energy Use (10^{12} Btu)**
Integrated	60.0	1.3	78
EAF-Flat Rolled	12.5	6.7	84
EAF-Other	36.0	6.7	241
Total			*403*
Finishing[c]			
	Amount (10^6 tons)	**Energy Intensity (10^6 Btu/ton)**	**Total Energy Use (10^{12} Btu)**
Integrated	58.4	4.36	255
EAF-Flat Rolled	11.5	2.07	24
-EAF-Other	32.5	2.44	79
Total			*358*
Totals			
	Amount (10^6 tons)	**Energy Intensity (10^6 Btu/ton)**	**Total Energy Use (10^{12} Btu)**
Integrated	58.4	20.66	1,207
EAF-Flat Rolled	11.5	9.51	109
EAF-Other	32.5	9.94	318
Grand Total			***1,634*** **10^{12} Btu *(or 15.9 MBtu/ton)***

a Good practice data for ironmaking includes pelletizing; includes lime production (6.1 10^6 tons x 6.25 MBtu/ton = 0.038 Q); oxygen production (3 x 10^8 1,000 scf x 17 kWh/1,000 scf x 10,500 Btu/kWh = 0.054 Q)

b Excludes on-site energy generation

c Includes at least 2 million tons of imported semi-finished steel

According to Stubbles, the average energy per U.S. shipped ton will decline by 2010 from the present 18.1 MBtu/ton to 15.0 MBtu, while total energy will drop from 1.83 quads to 1.57 quads. This reduction reflects both structural and process changes and includes the energy required to produce off-site pellets (70 million tons), oxygen, and lime as well as the energy associated with imported coke (6 million tons). The figure drops significantly (about 2 MBtu/ton or 0.21 quad) when the pellets, oxygen, and lime are excluded. It should be noted that Stubbles made his predictions in 2000; as of 2003, total industry energy consumption had dropped to 1.6 quads.

Table 6 summarizes the distribution of the projected energy reduction per net ton of shipments from 2000 to 2010 between the various types of facilities according to structural and technological changes in the industry. Replacement of inefficient blast furnaces, coupled with the potential fuel rate reduction in the remaining furnaces (due to tuyere injectants and burden materials), dominates the energy-reduction picture. Improving the efficiency of reheating through technology and sophisticated scheduling is also key.

Table 6. Stubbles Study Results: Projected Energy Reduction for U.S. Industry (2000 – 2010)

Process	Energy Savings from Structural Changes (10^6 Btu/ton)	Energy Savings from Technology Changes (10^6 Btu/ton)	Total Energy Savings (10^6 Btu/ton)
Integrated			
Blast furnace fuel	0.6	0.3	0.9
Reheating	--	0.2	0.2
Motor program	--	0.1	0.1
Cogeneration	--	0.1	0.1
Miscellaneous	0.1	0.4	0.5
Total	0.7	1.1	1.8
Average Energy Intensity for Production of 50 Million Tons = 20.0 10^6 Btu/ton			
EAF Long Products			
Melting	0.6	0.4	1.0
Reheating	--	0.1	0.1
Motor program	--	0.05	0.05
Miscellaneous	--	0.2	0.2
Total	0.6	0.75	1.35
Average Energy Intensity for Production of 30 Million Tons = 10.5 10^6 Btu/ton			
EAF Flat Products			
Melting	--	0.15	0.15
Reheating	--	0.07	0.07
Strip casting	--	0.15	0.15
Motor program	--	0.02	0.02
Miscellaneous	--	0.06	0.06
Total	--	0.45	0.45
Average Energy Intensity for Production of 25 Million Tons = 10.3 10^6 Btu/ton			
Total Industry Weighted Average for Production of 105 Million Tons = 15.0 10^6 Btu/ton			

The Steel Industry Energy Bandwidth

The results of the Fruehan and Stubbles studies provided the majority of the data required for the steel industry bandwidth analysis. Additional data on grinding, reheating, and hot rolling were derived from other sources. Tables 7 and 8 show the energy bandwidth data for ore-based steelmaking and electric arc furnace steelmaking, respectively.

Table 7. Energy Bandwidth Data for Ore-Based Steelmaking: Hot Metal Production and Reheating/Rolling (10^6 Btu/ton)

Process/ Category	Theoretical Minimum	Practical Minimum)	Industry Average	Good Practice	2010 Projected
Hot Metal (pellets and coke)	10.9[a]	11.4[b]	16.2[c]	15.5[d]	15.2[e]
Hot Metal (pellets and coal)	10.1[f]	10.6[g]	N/A	N/A	N/A
Hot Metal (fine ore and coal)	8.6[h]	9.1[i]	N/A	N/A	N/A
Reheating/ Hot Rolling	0.01[j]	0.8[k]	2.3[m]	2.3[n]	2.1[p]

a Liquid hot metal absolute minimum from Table 2 (8.5 MBtu/ton product) plus cokemaking theoretical value from Table 3 (1.7 MBtu/ton coke x 0.45 ton coke/ton iron = 0.8 MBtu/ton iron product) plus ore agglomeration theoretical value from Table 3 (1.0 MBtu/ton ore x 1.6 ton ore/ton iron = 1.6 MBtu/ton iron product)

b Liquid hot metal practical minimum from Table 2 (9.0 MBtu/ton product) plus cokemaking theoretical value from Table 3 (1.7 MBtu/ton coke x 0.45 ton coke/ton iron = 0.8 MBtu/ton iron product) plus ore agglomeration theoretical value from Table 3 (1.0 MBtu/ton ore x 1.6 ton ore/ton iron) = 1.6 MBtu/ton iron product)

c Liquid hot metal actual requirement from Table 2 (11.7 MBtu/ton product) plus cokemaking actual requirement from Table 3 (5.15 MBtu/ton coke x 0.45 ton coke/ton iron = 2.3 MBtu/ton iron product) plus ore agglomeration actual requirement from Table 3 (1.4 MBtu/ton ore x 1.6 ton ore/ton iron = 2.2 MBtu/ton iron product)

d Table 5 BOF ironmaking value for the BF/coke process route

e Good Practice Value minus integrated "energy savings from technology changes" blast furnace fuel values from Table 6

f Liquid hot metal absolute minimum from Table 2 (8.5 MBtu/ton product) plus ore agglomeration theoretical value from Table 3 (1.0 MBtu/ton ore x 1.6 ton ore/ton iron = 1.6 MBtu/ton iron product)

g Liquid hot metal practical minimum from Table 2 (9.0 MBtu/ton product) plus ore agglomeration theoretical value from Table 3 (1.0 MBtu/ton ore x 1.6 ton ore/ton iron = 1.6 MBtu/ton iron product)

h Liquid hot metal absolute minimum from Table 2 (8.5 MBtu/ton product) plus grinding value of 0.1 MBtu/ton from Energy Analysis of 108 Industrial Processes by Harry Brown

i Liquid hot metal practical minimum from Table 1 (9.0 MBtu/ton product) plus grinding value of 0.1 MBtu/ton from Energy Analysis of 108 Industrial Processes by Harry Brown

j Table 4 flat carbon slab (either 25.4 or 5.0 cm) cold rolling value; assumes hot rolling theoretically not needed

k Data from Table 2 (hot rolling flat practical minimum value); assumes no energy or yield losses

m Hot rolling flat actual requirement from Table 2 (1.9 MBtu/ton) plus electrical generation and transmission losses of 0.4 MBtu/ton

n *Energy and Environmental Profile of the U.S. Iron and Steel Industry,* Table 1-7 value for hot rolling/reheating

p Good Practice Value minus integrated "energy savings from technology changes" reheating value from Table 6

Table 8. Energy Bandwidth Data for EAF Steelmaking: Liquid Steel Production and Reheating/Rolling (10^6 Btu/ton)					
Process/ Category	**Theoretical Minimum**	**Practical Minimum**	**Industry Average**	**Good Practice**	**2010 Projected**
Liquid Steel (long products)	3.4[a]	4.3[a]	6.7[b]	6.7[b]	6.3[c]
Liquid Steel (flat prod)	3.4[a]	4.3[a]	6.7[b]	6.7[b]	6.6[c]
Reheating/ Hot Rolling (long)	0.01[d]	0.8[e]	2.4[f]	2.4[f]	2.3[g]
Reheating/ Hot Rolling	0.01[h]	0.8[e]	2.1[f]	2.1[f]	2.0[g]

a Data from Table 2, adjusted to include electrical transmission and distribution losses
b Table 5 EAF steelmaking value (for both flat rolled and long product)
c Good Practice Value minus EAF "energy savings from technology changes" melting values from Table 6
d Table 4 bar carbon value; assumes hot rolling theoretically not needed
e Data from Table 2 (hot rolling flat practical minimum value); assumes no energy or yield losses
f Table 5 EAF finishing values - note these numbers include other finishing operations after hot rolling
g Good Practice Value minus EAF "energy savings from technology changes" reheating value from Table 6
h Table 4 flat carbon slab 5.0 cm thick; assumes hot rolling theoretically not needed

The data in Tables 7 and 8 are illustrated in Figure 1, the energy bandwidth for the processes of hot metal production (from pellets and coke), BOF steelmaking, EAF steelmaking (long products), EAF steelmaking (flat products), and reheating/hot rolling. It is anticipated that the savings "band" between today's actual energy use and the 2010 projected value will be achieved without additional intervention through structural changes and existing emerging technologies. Therefore, the area of opportunity for achieving energy savings over the next ten years for each process shown in Figure 1 is the band (shown in red) between the practical minimum energy requirements and the 2010 projected energy use. Table 9 summarizes this opportunity for the four processes shown in Figure 1 and also shows the potential energy savings associated with the production of hot metal from fine ore and coal compared to the conventional pellet and coke-based route. It should be noted that the economic feasibility of realizing these savings opportunities has not been determined.

Table 9. Energy Savings Opportunity Identified from the Steel Energy Bandwidth	
Process	**Savings Opportunity (10^6 Btu/ton)**
Hot metal production (pellets and coke)	3.8
Hot metal production (fine ore and coal) as compared to hot metal production from pellets and coke	6.1
EAF steelmaking (long products)	2.0
EAF steelmaking (flat products)	2.3
Reheating/hot rolling	1.3

Figure 1. Steel Industry Energy Bandwidth